1. NEHRP Final Technical Report Grant number G19AP00013:

Identifying Faults and Earthquakes, and their Potential Association with Mass Wasting Along the Seal Cove Strand of the San Gregorio Fault in San Mateo County

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2. Abstract:

Geomorphic, geochronologic and tectonic data collected along the San Gregorio Fault where it comes ashore along Pillar Point Bluff and Seal Cove in San Mateo County, California identifies several new fault strand exposures of the San Gregorio Fault, collectively referred to as the Middle Strand, that trends down the middle of Pillar Point Bluff. The Middle Strand is exposed along a landslide headscarp more than 100 m in length and up to 10 m in height and exhibits significant oblique slip. Here the fault deforms Pliocene Purisima Formation bedrock, which forms a wavecut platform, and late Pleistocene marine terrace deposits. Fault gouge in the Purisima Formation up to 1.5 m wide and displacements in the overlying marine terrace deposits that extend into soil horizons are used to develop a revised picture of the faulting style and role of this fault strand. Initial IR-IRSL and cosmogenic terrestrial dates suggest formation and abandonment of ~55 ka and ~11-18 ka, respectively, of the marine terrace. These exposures and further mapping of surface deformation and consultant trench-identified faults along the San Gregorio Fault suggest along strike changes in fault geometry may be controlling surface morphology. We observe a positive flower structure forming along a restraining bend of the fault that transfers slip to the Seal Cove Fault through a releasing stepover. These observations and initial dates bring into question previous assumptions of the fault structure within this on-land section of the San Gregorio Fault and indicate that subsurface fault geometry likely plays a significant role in surface morphology.

3. Report:

NEHRP funding supported (1) initial geomorphic mapping, (2) and initial dating of distinct coastal and fluvial sediment horizons of a marine terrace expressed along an unstudied strand of the San Gregorio Fault at Pillar Point Bluff in San Mateo County, CA (Figure 1a and 1B). In the following sections, we summarize initial results for (1) and (2).

(1) <u>Initial geomorphic mapping</u>

Field mapping combined with a recently excavated “trench wall” by our team, initiated by at Pillar Point Bluff confirms the Middle Strand fault mapped as an inferred fault by Pampeyan, 1981 (Figure 1C). This Middle Strand aligns with the Seal Cove Fault, faults mapped in consultant trenches in the Seal Cove area and with a series of gravity spreading ridges along its strike

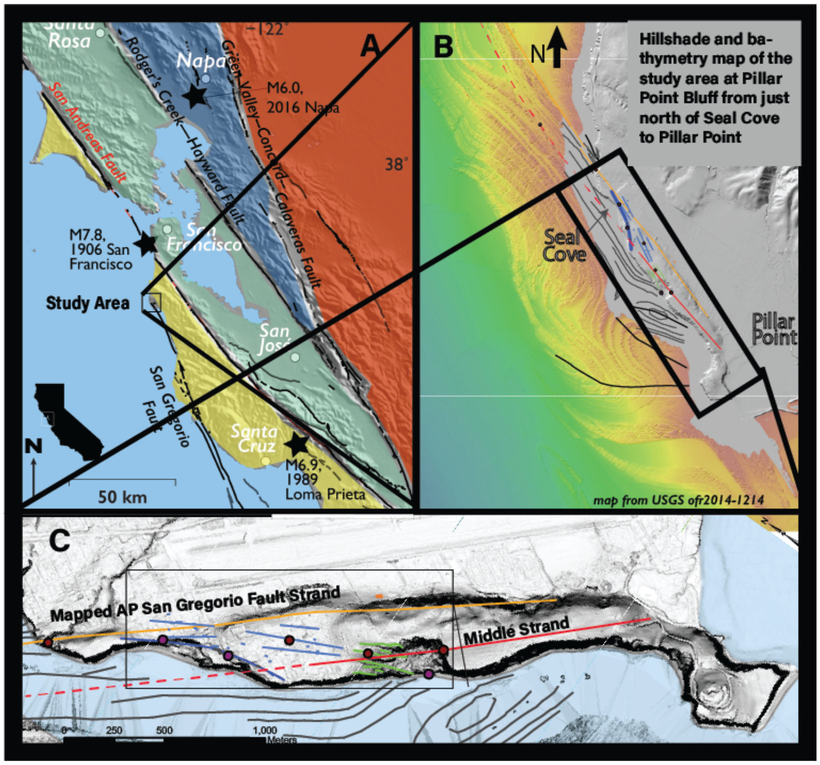

Figure 1. A. Location of the study area relative to faults that make up the northern San Andreas Fault system, shown as crustal blocks. B. Hillshade and bathymetry map at Pillar Point Bluff showing folding offshore in the Purisima Formation and the location of faults that deform Pillar Point Bluff. C. Hillshade of Pillar Point Bluff and mapped faults. The orange line is the mapped AP fault, the red line is the Middle Stand, which is the focus of this study, the blue and green lines are faults and gravity spreading ridges collected from consultant reports through the county office in San Mateo County.

to define a set of stepover faults (Figure 1C), supporting lineations reported by Leighton (1971) and Pampeyan (1981). The light blue fault lines in the Seal Cove region are separated from each other and from the green gravity spreading ridges in Figure 1C, however, it is believed the good alignment and arrangement of the three sets indicate they form a series of through-going faults. The consultant-reported faults are detailed in Appendix A. The trend of the Middle Strand from the southeast end of Pillar Point Bluff, where it comes ashore west of the Pillar Point Marsh, to the fault exposure in the middle of Pillar Point Bluff is along about a 319° azimuth.

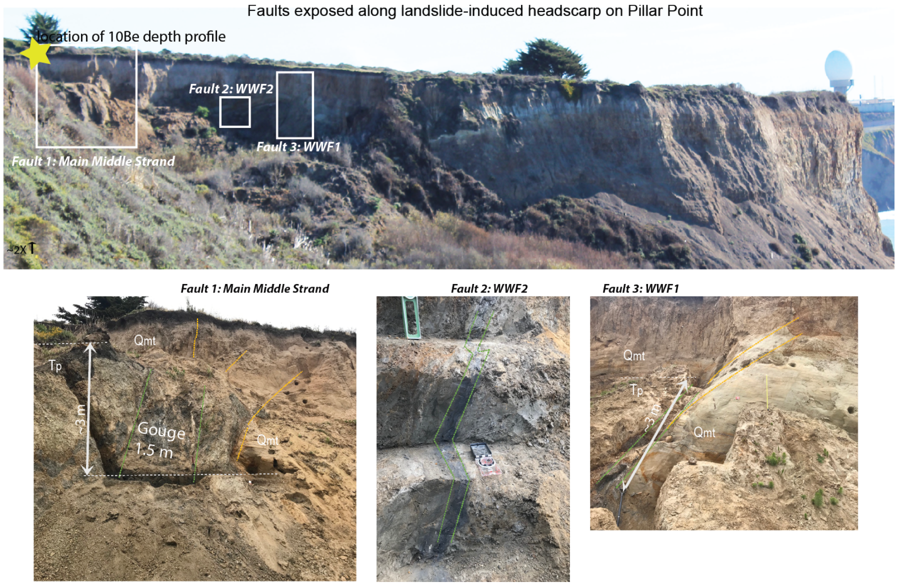

Figure 2. Field photos of the landslide headscarp exposing the Middle Strand and evidence of faulting within the marine terrace. Location of samples collected for 10Be dating is shown by the yellow star. The triangles in the top photo show the locations of 3 faults obliquely displacing fluvial and coastal sediments that make up the marine terrace. Please see text for details.

Trench Wall Middle Strand Exposures:

To map the stratigraphy at Pillar Point Bluff, we cleaned off the wall of an existing landslide headscarp. Figure 2 shows a cross-sectional view of the Middle Strand looking southeast perpendicular to the trend of the fault along this wall is located near the center of Pillar Point Bluff. The “trench wall” is approximately 100 m long section of the landslide wall with vertical sections up to 7 m high.

Four components of the Middle Strand are identified along the trench wall, the main fault (MF) which includes branching faults that emanate from the MF and continue at a low angle into sediments that make up the Quaternary marine terrace (Qmt). These faults are here identified as Low Angle Adjacent Faults, LAAF, the near west wall (WWF2), the west wall (WWF1), and the far west wall (FWWF), Figure 2. The eastern-most component, identified as the “main fault”, aligns with a gentle scarp that runs down the middle of Pillar Point Bluff and exhibits the widest clay gouge zone in bedrock and the largest apparent horizontal offset judging from lithology difference. The gouge zone in the bedrock Purisima layer is 1.2 m wide (Figure 2) with vertical foliations displaying sub-horizontal striations and which dips sub-vertically (80^{o} NE $\pm$ 10^{o}). Freshly exposed black gouge is a high viscosity moist clay that emits a noticeable odor of petroleum. Once exposed the black clay gouge desiccates to vertically foliated plates with visible striations (slickensides) under a microscope.

West of this main fault zone, designated MF, are two additional fault strands that have been exposed, WWF1 and WWF2, and one inferred fault, FWWF. WWF2 is shown in Figure 2. The vertical offset of the Purisima for WWF1 is ~4.2 m, and the offset in lithology of the marine terrace deposit is somewhat less than that for MF, while there is very little vertical offset and negligible lithology change across WWF2.

(2) Initial dating of distinct coastal and fluvial sediment horizons of a marine terrace

IR-IRSL and ^{10}Be dates at Pillar Point Bluff indicate deposition of sediment above the wavecut platform occured ~52.6 ka and final abandonment of the surface at 11-18 ka. A total of 5 IR-IRSL samples were collected from varying depths within different stratigraphic sandy units that make up the Qmt and 5 samples were collected for a ^{10}Be depth profile from fluvial sediments of course alluvium along the “trench wall” (Figure 2). Measured concentrations of the ^{10}Be depth profile collected from Pillar Point Bluff shows a decrease with depth (Figure 3). The ^{10}Be depth profile produced a model age of ~52.6 ka (Table 1). One amalgamated sample, composing of small gravels, from the surface of Pillar Point Bluff yielded and exposure of ~18.8 ka, when corrected for inheritance. This inheritance correction was derived from the depth profile model age (Table 2).

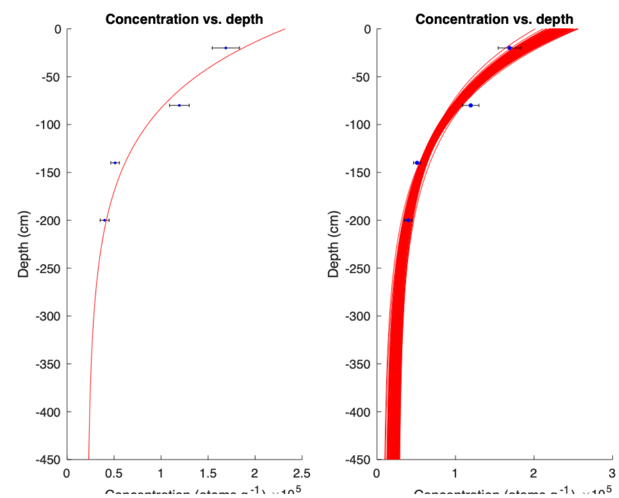

Figure 3. Results from simulating ^{10}Be concentration versus depth following the methods in Hidy et al. (2010). Left panel shows the lowest chi-squared fit model curve of measure ^{10}Be concentrations vs. depth. The right panel shows the 2σ solution spaces (red region) of measured ^{10}Be concentrations vs. depth.

Table 1 Summary of age, inheritance, and denudation rate statistics derived from simulating ^{10}Be concentrations for Terrace at Pillar Point Bluff

Pillar Point Terrace	Age (ka)	Inheritance (10^4 atoms g^{-1})	Denudation rate (cm ka^{-1})
Mean	54.6	1.46	0.10
Median	54.5	1.47	0.11
Mode	54.3	1.45	0.16
Lowest C^2	52.6	1.62	0.12
Maximum	69.4	2.77	0.20
Minimum	43.5	0.01	0.00

[a]Input paramenters include:

Shielding factor is aproximated as 1. No Shielding factor data was collected

Cover is approximated as 1.

Production rate scaling scheme following Lal(1991) and Stone(2000).

Depth of moun fit is 5 m.

Total production rate error is treated as a contstant value of 4.53529 (atoms/g/a)
Bulk denisty was aproximated using an average soil, with a denisty of 2.1 from 0-30cm depth, 2.2 at 60cm depth, and 2.0 from 100-180cm depth. No density data was collected

Erosion rate is 0 cm/ka for minimum and 0.2 cm/ka for maximum based on terrace geomophology, but soil stratigraphy has not been considered

Erosion threshold is 1 cm.

Inheritance is 0(atom/g) for minimum and 30,000(atom/g) for maximum.

Attenuation length of neutrons is 160 ± 5 g $cm^{3.}$

Number of simulations, 100,000.

Table 2. Ages of ^{10}Be samples from Pillar Point Bluff. Sample concentrations, ages, and uncertainties are displayed. Ages have not been fully adjusted Ages of samples calculated using CRONUS-Earth online calculator version 2.3 using Lal (1991) / Stone (2000) scaling scheme for spallation.

Sample	^{10}Be (atoms/g)	Uncertainty (atoms/g)	Exposure Age (yr)	Uncertainty (yr)
SGF-2E	71,857	2,315	18,824	± 1726

Ages determined from Pillar Point Bluff sediment samples using IR-IRSL techniques are shown in Table 3. Calculations were performed by the UCLA Luminescence Laboratory. Ages were calculated using the DRAC 1.2 online calculator (Durcan et al., 2015). Higher elevation samples have younger ages along the vertical profile SG19-03—SG19-04—SG19-05 (Figure 3), showing the pattern expected for depositional contacts. The neighboring profile SG19-00—SG-00A shows a similar pattern, with the higher elevation sample having a younger age (These two samples are on opposite sides of the fault, 00 is on the same side as and below 03 and 04). However, ages are not laterally consistent. Lack of lateral continuity suggests that the layers are offset.

Figure 3. Field photo showing the location of IR-IRSL samples collected from Pillar Point Bluff

Table 3. IR-IRSL ages from Pillar Point Bluff. Equivalent dose values were determined according to an IR-IRSL protocol (Buylaert et al., 2009) and calculations were performed using DRAC 1.2 online calculator (Durcan et al., 2015). Processing and calculations were performed at the UCLA Luminescence Laboratory.

Sample	Age (ka)	Uncertainty (ka)
SG19-00	47.73	± 4.11
SG19-03	50.61	± 3.44
SG19-00A	38.09	± 6.05
SG19-05	11.41	± 1.54
SG19-04	40.28	± 7.06

Ages of luminescence samples determined at UCLA Luminescence Laboratory.

Discussion:

Results from IR-IRSL dating at Pillar Point Bluff suggest that these sediments were likely vertically offset by earthquakes sometime after ~50 ka and least two faults that have offset sediment horizons dated to ~11-18 ka, indicating possibly faulting and earthquakes during Holocene time. Dates calculated from IR-IRL data support east-side-up motion along multiple fault strands (Figure 3). Very fine-grained black fault gouge clay can also be seen in Figures 2 and 3, showing the location of one of the major strands. South of Pillar Point Bluff we propose the San Gregorio Fault comes from the southeast along about a 331^{o} $\pm$ 2^{o} azimuth, in agreement with Johnson et al (2018), then abruptly takes a left step to the west ~12^{o} to follow the Middle Strand at the south end of Pillar Point Bluff. An earlier study by Koehler et al. (2005) suggested that Pillar Point Marsh was a pull-apart basin formed by a right stepping of the right lateral San Gregorio Fault from where the San Gregorio Fault comes ashore to the mapped scarp along the Pillar Point Bluff eastern scarp on the southern end of Pillar Point Bluff. This study found evidence of sudden subsidence to support that assumption (Koehler et al., 2005). We speculate that the subsided layers were all quite thin, typically less than 10 cm, and such subsidence and/or settling could likely also have occurred adjacent to a fault in a near-shore sedimentary basin by an earthquake along the San Gregorio Fault, including the Middle Strand, without the requirement for a right stepover at the southern end of Pillar Point Bluff. The southern side of the Koehler et al (2005) proposed pull-apart basin is actually the sea bottom which is lower than the marsh and there is no evidence of stratigraphic relief in buried layers in that direction, although any potential wave-caused erosion could make it difficult to analyze the geomorphological development of this area. Whether the San Gregorio Fault includes both paths on this end, the Middle Strand and the Seal Cove strand (that is, whether the Seal Cove fault includes strike-slip motion or is primarily dip-slip), is not clear.

From a regional perspective the San Gregorio Fault goes through a double-restraining bend with the southeastern bend being $12 \pm 2^{\circ}$ and the northwestern bends about $17 \pm 4^{\circ}$ (Johnson et al, 2018 and our new mapping). The trend of the Middle Strand from the southeast end of Pillar Point Bluff, where it comes ashore west of the Pillar Point Marsh, to the fault exposure in the middle of Pillar Point Bluff is along about a 319° azimuth. Proceeding northwest the Middle Strand bifurcates. One component continues along the 319° trend going offshore at the south end of Seal Cove along one or the other of the proposed paths in Figure 2 and is evidenced by an offset Purisima layer in Seal Cove and further folding structure northwest of there where it turns northward as seen in Figure 2. A second component right-steps through a series of faults oriented about $15 \pm 10^{\circ}$ clockwise to the middle strand, suggestive of Riedel R-shears for right-lateral movement, over to where it merges with the previously identified strand that exits in the sea cliff of Fitzgerald Marine Preserve (the "Fitzgerald Fault") and then continues NW along about a $320 - 326^{\circ}$ trend (Figure 2).

Conclusions:

The Middle Strand of the San Gregorio Fault along the on-land section from Pillar Point to Moss Beach has been investigated and evidence indicates it includes a right stepover that connects this Middle Strand with the previously identified exposures by Simpson et al, 1997, and in the sea cliff at Fitzgerald Marine Reserve. An exposure of the fault has been aided by a fortuitous location of a landslide headscarp that allowed easy further exposures that have been used to characterize the nature of the fault. The Middle Strand fault exposure is seen in both the bedrock Purisima formation, Tp, and a wavecut platform cut into it and also an unconformably overlying marine terrace deposit, Qmt. There have been at least four to six fault paths in a main fault since the wavecut platform was abandoned ~38 – 55 (certainly the wavecut platform was abandoned at 50ka, maybe the surface was abandoned at 11-18ka) ka. The conclusion is that Pillar Point Bluff and the Seal Cove area of Moss Beach are perforated and highly influenced by fault strands. The preponderance of mass wasting evident in the Seal Cover area of Moss Beach is thus thought to be initiated along and influenced by faults.

Appendix A: Geotechnical Reports for Seal Cove

This is a summary of data derived from consultant's geotechnical reports for the unincorporated Seal Cove area of Moss Beach, California, Table AI and Figure A1. The reports are available from the Planning Department of San Mateo County, although are not accessible on-line. We here also include mapping of other features including stress shears in roadbeds, complementary pairs of arcuate extension cracks (explained in Appendix C), and faults identified by other investigators; Simpson et al, 1997, Koehler et al, 2005, Leighton and Associates, 1971, Cotton and Associates, 1981, Pampeyan, 1991.

Table I. Moss Beach Geotechnical Reports Summary:				Report	Estimated from report			V Strong Evid?
No.	APN	Address	Consultant	Year	nom. UTM coords		Azimuth	eg vert offset
					Easting	Northing	Strike, deg	
1	37225100	1015 Park Way	William Jones Inc Cons Eng	1983	543095	4152748	318	
2	37221170	171 Alton Ave	Hydro-Geo Consultants	1991	543056	4152709	320	Y
3	37221170	171 Alton Ave	Hydro-Geo Consultants	1991	543047	4152700	320	
4	37221170	171 Alton Ave	Hydro-Geo Consultants	1991	543043	4152693	320	
5	37221140	140 Cypress Ave	JCP 1079	1983	543035	4152700	340	Y
6	37221020	120 Cypress Ave	Sigma Prime	2017	543006	4152666	325	
7	37196100		Simpson et al, 1997	1997	542983	4152699	325	
8	37196100		Simpson et al, 1997	1997	542975	4152684	340	
9	37222100	1040 Park Way			543082	4152691	328	
10	37222200	191 Marine Blvd	Sigma Prime Geosciences	2014	543096	4152661	313	Y
11	37223190	160 Marine Blvd	Sigma Prime mapped		543130	4152604	330	
12	37223190	160 Marine Blvd	Sigma Prime mapped		543136	4152583	330	
13	37223190	160 Marine Blvd	Sigma Prime mapped		543110	4152596	328	
14	37223140	159 Orval Ave	Sigma Prime mapped		543109	4152583	335	
15	37222160	x 115 Marine Blvd	Sigma Prime mapped		543062	4152583	335	
16	37215100	120 Beach Way	Lettis Assoc	2019	543033	4152548	335	
17	37223240	135 Orval Ave			543106	4152528	330	
18	37259270	871 San Ramone Ave	Purcell, Rhoades & Assoc	1976	543271	4152296	350	
19	37259270	871 San Ramone Ave	Purcell, Rhoades & Assoc	1976	543255	4152294	350	Y
20	37258100	837 Ocean Blvd	Baldwin-Wright Geotechnical Consultants	1989	543163	4152189	355	Y
21	37284170	150 Madrone			543264	4152167	325	
22	37285180	140 Precita Ave	GEC map, Wood 1984	1984	543338	4152149	335	
23	37285100	121 Bernal Ave	GEC map, Wood 1984	1984	543364	4152106	335	
23	37285100	121 Bernal Ave	GEC map, Wood 1984	1984	543357	4152121	335	
24	37287030	991 San Ramon Ave	JCP Eng	1988	543418	4152153	336	
25	37286030	140 Bernal Ave	JCP 1029	1983	543437	4152114	332	
26	37281160	75 Bernal Ave	GEC map, DGH 1979	1979	543361	4152055	330	
27	37281160	75 Bernal Ave	GEC map, DGH 1979	1979	543337	4152037	335	
28	37282070	90 Bernal Ave	GEC map, PSC 1979	1979	543404	4152052	330	
29	37282070	90 Bernal Ave	? Wood/Steve Deal Assoc/PSC	1984	543391	4152029	328	
30	37282090	70 Bernal Ave	GEC map, JCP 1985	1985	543364	4152003	330	
31	37282080	50 Bernal Ave	GEC map, JCP 1985	1985	543351	4152003	339	Y
32	37282080	50 Bernal Ave	Geoforensic and Earth Consul Map, JCP 1985	1985	543365	4151979	340	

Table AI: Trenching-identified faults by commercial geo-consultants. APN is San Mateo County Assessor's parcel number.

A large portion of Moss Beach is within a short distance of the Seal Cove Fault, part of the Alquist-Priola special fault zones designated by California Geological Survey, 2018, to require geological investigations for habitable construction.

All faults identified in consultant reports found during this study review are included, although it is noted that some of these identifications have been questioned by other consultants and others have been the subject of disputes, and not all consultant reports were found. Two sources, Sigma Prime and GEC (Geoforensics and Earth Consultants), provided maps of faults they had compiled and are indicated in the table. It is also acknowledged that precise location of faults is not always readily accomplished from the reports and in several cases the locations derived from the trench map is adjusted to account for the actual house location. That is, it is assumed that following a geotechnical study for a particular lot the subsequent house (excluding the garage) on that lot was positioned in conformance with the required 10ft exclusion distance and if my reading of the trench map did not result in that margin then I assumed the actual siting of the house was accurately done to the real location of the fault and was thus a better location guide. A house positioned at an odd angle relative to the lot or with a corner cut off is a certain sign it was aligned to fault constraints. No adjustment was made if the projection of a fault goes under a neighboring house, a common occurrence. While it is believed most faults are located within about 3 meters of the trench-identified location, in some cases the location was adjusted up to 10 meters. Figures A2 and A3 are expansions of the mapping for more detailed identification with fault numbers added corresponding to the sequence number in Table AI.

Few of the consultant-reported faults exhibit significant lithology changes or strata offsets across the faults and none included an exposed Purisima bedrock. The requirement to be recorded as a fault is that they exhibit a noticeable fracture or fault trace that extends to the bottom of the trench which is typically 6 to 10 feet deep. All reported faults are included in this mapping while those few with stronger evidence, such as a noticeable lithology change, vertical strata offset, or wide soil-filled cracks, are so noted in the last column of Table AI.

It may be noted that for the exposed faults described in this report if trenches had only been dug 6 to 10 feet into the marine terrace deposit, Qmt, several of the faults would not have been noticed, or noticed as minor cracks and many would not show obvious lithology offsets even though some of those faults are here traced to the Purisima where they show clear faulting with fault gouge zones up to and over a meter with significant vertical offsets. There is often reported skepticism for the findings of the geotechnical reports because the requirement for calling features a fault appears overly inclusive. However, one lesson of this report appears to be that fault evidence in Qmt, as often reported in consultant reports, likely is an indicator of faulting in the underlying bedrock, but does not necessarily fully reflect the degree of faulting in the bedrock, and the absence of faulting in upper levels of Qmt does not necessarily translate to absence of faulting in bedrock, although, of course, may indicate absence of recent faulting.

The consultant faults generally align in a few linear groupings delineated by the yellow lines in Figure A1. It is of interest to compare these trends with an earlier map by Leighton et al, 1971, where they mapped "lineations" from aerial photographs. These are the gray lines in Figure A1 and are similar (perhaps the same) as those mapped by Pampeyan, 1991. The two eastern Leighton lineations reasonably follow the trends of consultant-identified faults in the Seal Cove highlands. The western-most of the Leighton lineations does not match any consultant faults here recorded, however, few trenching studies have been done in the western section of the

Seal Cove Highlands since that area apparently is far enough from the A-P line not to require such. Rather, only a few soil studies were done in that area. Thus, the lack of consultant-identified faults cannot be taken to imply there are not faults there. There is some coincidence between the Leighton western lineation and roadbed shears but not enough to conclude there is a correlation. The relationship between the Leighton lineations and the consultant-identified faults in the Seal Cove lowlands is not as clear. The eastern-most lineation was not extended beyond its intersection with the AP line and the center lineation deviates most from the consultant fault trend in an area that is topologically saddle shaped and following the lineation in that area may not have been obvious.

Some of the gravity spreading ridges, the green lines on the north side of the large landslide area in Figure A1 and south of the developed area, likely also align with the consultant fault trends. The two longest ridges appear to align with the two best-defined consultant fault trends. Extending both sets of lines the 100 meters that separate them would result in close matches in both location and direction. The two long ridges are also the highest and most pronounced ridges, up to 2 m high and 10 m wide, and are traceable the furthest toward the developed area. Only the uphill-facing scarp is plotted for each spreading ridge, but there is also a corresponding subparallel downhill-facing scarp for each of the ridges. The width of the ridge is roughly the width of the plot line. Leighton did not extend his lineations past the designated development area, Bernal Avenue being the last street developed, so we don't have the benefit of his lineation interpretation in the intervening area, and no trenching has been done in this area either. Currently, the heavy undergrowth prevents a confident surface topology mapping in this area absent a high-definition lidar map, but the alignment of trends are strongly suggestive of a continuation of the faults causing the gravity spreading ridges into the consultant fault trends. Similarly, the alignment of the two consultant fault trends in the lowlands with those in the highlands suggests they may also be connected thereby forming multiple fault paths from the large landslide area, where the Middle Strand has been exposed, across to the AP fault line and on to the Fitzgerald Fault exposed at the shoreline.

The additional gravity spreading ridges could only be mapped over shorter distances and they are smaller in height and are without clear fault extensions in the developed area. The term "gravity spreading ridge" was used when first mapping these ridges, however, while the term is descriptive and continues to be used and they may look similar to such structures, also called Sackungen (Varnes et al, 1989), it is now felt that term may imply an origin not consistent with our current understanding of these faults. These ridges are now though to be tectonic in origin and not just due to gravitational forces.

In summary, the fault trends, lineations, spreading ridges and shears throughout Moss Beach and Pillar Point Bluff indicate the area is generally perforated by faults, but that particular trends are apparent and are instructive as discussed throughout this report.

Subsurface faults in developed areas of the unincorporated Seal Cove and Moss Beach areas were mapped from numerous trench-aided geologic consultant reports from the Geotechnical Office of the San Mateo County Planning Department. The consultant reports are a result of much of this area being within the Alquist-Priolo special studies zone for the San Gregorio Fault which requires geologic studies in order to build structures in California (California Geological Survey, 2018).

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(4) **Bibliography: None**

(5) **Acknowledgement of Support.** The generous assistance and expert consultation of Jean DeMouthe (deceased) who was the San Mateo County Geotechnical Officer at the time of most of the consultant report data collection is gratefully acknowledged and much appreciated.